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ABSTRACT

Recent research shows that students' understanding of many scientific topics is influenced by misconceptions that conflict with accepted scientific theories and persist even after instruction. In this study, student misconceptions were identified and used as a basis for analyzing the classroom behavior of teachers and students and for developing modifications that increased the effectiveness of commercial science programs. Results, obtained from case studies of teachers using either the light unit from Laidlaw Brothers "Exploring Science" textbook or the Producers part of the Science Curriculum Improvement Study (SCIS-II) "Communities" unit, indicated that: most students had misconceptions; the teachers exhibited a variety of teaching styles that did not take student misconceptions into account; and fewer than one quarter of the students learned the scientific conceptions they studied. When teachers used modified materials (which informed them about likely student misconceptions and suggested strategies for helping students to change), important changes in the teachers' behavior were noted and at least three times as many students understood the scientific conceptions of light than in the previous year. Learning for the Producers part did not improve, but other problems with the part were identified. When these problems were addressed in a subsequent study, learning improved substantially. (Author/JN)

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Research Series No. 147

THE PLANNING AND TEACHING INTERMEDIATE SCIENCE STUDY: FINAL REPORT

Edward L. Smith and Charles W. Anderson

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Edward L. Smith and Charles W. Anderson

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Abstract

Recent research shows that students' understanding of a wide variety of scientific topics is influenced by misconceptions that conflict with accepted scientific theories and that persist even after instruction. In this study, student misconceptions were identified and used as a basis for analyzing the classroom behavior of teachers and students and for developing modifications that increased the effectiveness of commercial science programs. In Year 1, case studies were conducted of 14 teachers teaching either (a) the Light unit from Laidlaw Brothers' *Exploring Science* textbook, or (b) the Producers part of SCIIS or SCIS II *Communities* unit. Pretests revealed that most students had misconceptions. Classroom observations and teacher interviews revealed that the teachers exhibited a variety of teaching styles that did not take student misconceptions into account. Fewer than one quarter of the students learned the scientific conceptions they had studied. In Year 2, modifications were developed for both of the target units and used by 10 teachers. The modified materials informed teachers about likely student misconceptions and suggested strategies for helping students to change. Classroom observational data showed important changes in the teachers' behavior, and at least three times as many students understood the scientific conceptions of light than in Year 1. Learning for the Producers part did not improve, but other problems with the Producers part were identified. When these problems were addressed in a subsequent study, learning improved substantially.

THE PLANNING AND TEACHING INTERMEDIATE SCIENCE STUDY: FINAL REPORT[1]

Edward L. Smith and Charles W. Anderson[2]

The study of human thinking has undergone a revolution over the last 25 years. Developments in a variety of fields, including cognitive psychology, linguistics, and artificial intelligence, have converged to produce new and important insights into the nature of human cognitive processing. The common insights that have arisen from these developments form the basis for the new field of cognitive science (cf. Newell & Simon, 1972; Case, 1983; F. Smith, 1975). Two insights in particular lie at the core of this new understanding of human reasoning.

The first concerns the limitations of human beings as information processors. Compared to even an inexpensive computer, humans have extremely small working memories and process the information in short-term memory quite slowly. Thus humans are quite susceptible to information overload.

The second insight concerns the role that preexisting cognitive structure plays in perception, comprehension, and memory. Philosophers going back to Kant have emphasized that the nature of human perception and experience are determined by cognitive structures that exist before perception and experience. Recent research has produced an explosion of knowledge about those

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[2]Edward L. Smith and Charles "Andy" W. Anderson coordinated the Planning and Teaching Intermediate Science Study. Smith is an associate professor of teacher education, and Anderson is an assistant professor of teacher education. They would like to acknowledge the assistance of Lucille Slinger, Kathleen J. Roth, and Janet Eaton.

cognitive structures, which are variously called schemata (R. Anderson, Spiro, & M. Anderson, 1978; Rumelhart & Ortony, 1977), frames (Davis, 1981), alternative frameworks (Driver & Easley, 1978), and many other terms.

An important aspect of this recent research has been the discovery of how often these cognitive structures are inadequate or incorrect. In the field of science, for example, researchers have found that most people understand the motion of objects by using physical theories more closely akin to those of Aristotle or medievil theorists than to those of Newton or Einstein, (Di Sessa, 1982; McCloskey, 1983); that although students at the end of a high school chemistry course can often balance chemical equations, many have little or no understanding of what the symbols represent (Ben Zvi, Eylon, & Silberstein, 1982); and that young children who say, "The earth is round," may not be referring to the earth we live on at all (Nussbaum & Novak, 1976).

Overall, the picture that emerges is one of human beings as creatures of bounded rationality. What people do is sensible, but their comprehension and learning are limited both by the fact that they often depend on incorrect schemata or misconceptions and by the limits of their information-processing capacity.

In this study, we examined the implications of these findings about human cognitive processing for the teaching and learning of elementary school science. We believe these findings have important implications for both teacher education and curriculum development.

Methods

The methods used during each year of the two-year Planning and Teaching Intermediate Science (PTIS) Study are described below.

Year 1

Year 1 was devoted to naturalistic observation of teachers and students in fifth-grade classrooms. Case studies were conducted of nine teachers as they taught the Producers part of a revised version of the Science Curriculum Improvement Study (SCIS) *Communities* unit (SCIS, 1971). Seven of these teachers used the SCIIS version (Knott, Lawson, Karplus, Thier, & Montgomery, 1978); two teachers were using the SCIS II version[3] (Paldy, Amburgey, Collea, Cooper, Maxwell, & Riley, 1978). Case studies were conducted of five teachers as they taught the Light unit from the Laidlaw Brothers *Exploring Science* textbook (Blecha, Gega, & Green, 1979).

Each of the 14 case studies consisted of (a) pretests and posttests administered to the students, (b) observations that produced detailed narrative records of some or all of the lessons taught during the course of the unit, (c) interviews with the teacher, and (d) observations of teacher planning.

Year 2

The results from the first year's case studies were used as the basis for designing modifications in the two units. (The modifications are discussed later in this paper.) Case studies were conducted of four teachers using the modified Producers part and of six teachers using the modified Light unit.

Year 1 Results

What we saw during Year 1 could be described as universal failure. Even though most of the teachers who volunteered to participate in the study were

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[3]SCIIS and SCIS II are both revisions of the original SCIS program. For simplicity, all three programs will be referred to in this paper as SCIS. Anyone wishing to know which teachers used which version of SCIS may contact the authors.

dedicated, experienced, and able, there was not a single classroom in which even half the students came to understand the key concepts taught.

We attribute this failure of instruction to three types of information-processing problems that affected students and teachers. Two of these problems concerned the preexisting cognitive structures of students and teachers; both students and teachers were affected by misconceptions, beliefs that had negative effects on the way that they processed information in the classroom. In addition, teachers were limited in their ability to respond to the multiple demands placed on their information-processing capacity.

Misconceptions Among Students

Consistent with the growing body of research on student misconceptions in science (Helm & Novak, 1983; Driver & Erickson, 1983), our pretests and classroom observations revealed the existence of important student misconceptions about both light and plants as producers (C. Anderson & E. Smith, 1983a; Roth, E. Smith, & C. Anderson, 1983). In Table 1, these misconceptions are contrasted with the scientific conceptions presented in the commercial program materials. Also consistent with the misconceptions research, our posttests indicated that less than a quarter of the students had come to believe the scientific conception as a result of the instruction on either unit.

In addition, our analyses of classroom instruction documented ways in which student misconceptions contributed to these results. The students' misconceptions affected both their interpretation of instruction and their behavior (Eaton, C. Anderson, & E. Smith, 1984; E. Smith & C. Anderson, in press).

For example, one of the crucial experiments in the SCIS unit involved growing grass plants in the light and in the dark. Students' observations

that the plants in the dark began to grow and then wilted were designed to set the stage for the introduction of photosynthesis: The plants in the dark died because photosynthesis is their only source of food after the food stored in the seeds is used up, and they could not engage in photosynthesis without light. However, the students' misconceptions caused them to interpret the

Table 1
Contrast Between Common Student Misconceptions and Scientific Conceptions

Issue	Common Misconception	Scientific Conception
Light		
1. How do people see?	Light shines on or brightens objects so that people's eyes can see them directly.	People's eyes detect reflected light that has bounced off objects.
2. What is color?	Objects have colors. Light helps people to see those colors.	Color (wavelength) is a property of light. Objects appear colored because they reflect some colors of light while absorbing others.
Producers		
1. Where do plants get their food?	Plants take in their food in the form of water, fertilizer (plant food), and/or other materials.	Sprouting seeds use food stored in the cotyledons. Mature plants use light to make their own food.
2. Why do plants need light?	Plants need light to live and grow or be healthy.	Plants use light energy to make food, without which they cannot live.

experiment differently. Because they assumed that food for plants was water and other materials taken in from the environment, most students saw no connection between the experiment and the issue of where plants get their

food. Instead, they interpreted the pale and sickly appearance of the plants in the dark as support for their misconception: Plants need light in order to stay green and healthy. They saw no need for further explanation (E. Smith & C. Anderson, in press).

Our analysis of the text and teacher's guide for the Light unit indicated that the authors had no awareness of the conceptual-change problem. They provided no information about probable student misconceptions and no teaching suggestions to help address them. In fact, the choice of language in the text was often consistent with the misconceptions (Eaton, C. Anderson, & E. Smith, 1984). In contrast, the SCIS teacher's guide did include some information about misconceptions, and some of the teaching suggestions did appear aimed at attacking them. However, much of this strategy was implicit and buried in a myriad of procedural details (E. Smith & C. Anderson, in press).

Misconceptions Among Teachers

Classroom observations, observations of teacher planning, and interviews with teachers during Year 1 convinced us that the teachers were also affected by misconceptions. Unlike the students, whose crucial misconceptions were of science content, the teachers held misconceptions that were essentially pedagogical.

The teachers observed during Year 1 could be characterized as exhibiting one of three approaches to the teaching of science. Although these three approaches were quite different from each other, none of the 14 teachers we observed was particularly successful in getting students to abandon their misconceptions and understand the scientific theories. The three approaches were activity-driven teaching, didactic teaching, and discovery teaching.

Activity-driven teaching. Teachers using this approach focused primarily on the activities to be carried out in the classroom: textbook reading, demonstrations, experiments, discussions, and so on. The teachers were either unconcerned about or unable to determine the specific contribution of the activities to learning. They tended to assume that if they followed the recommendations of the authors of their textbook or teacher's guide, student learning would occur automatically. Student posttest results indicate that this assumption was unjustified; the activity-driven teachers often unknowingly modified or deleted crucial parts of the program, making it almost impossible for the students to learn the scientific theories.

Activity-driven teachers for whom case studies are available are Ms. Baxter (Eaton, C. Anderson, & E. Smith, 1984) and Ms. Ross (E. Smith & Sendelbach, 1982).

Ms. Baxter closely followed the *Exploring Science* textbook, reading the text with her class and doing the suggested experiments and demonstrations. She covered everything in the text and added a few supplemental materials and activities. She rarely planned more than one day ahead.

Although Ms. Ross believed that she was following the recommendations in the SCIS teacher's guide closely, Smith and Sendelbach found that she unintentionally diverged from those recommendations at numerous points. In particular, she tended to curtail or omit class discussions designed to help students think meaningfully about the activities they were doing. Her planning generally focused on materials and the timing of activities; she considered what her students might learn from those activities only if she had time in the few minutes immediately before class began.

With their heavy focus on management details, the activity-driven teachers were generally not aware of, or concerned about, their students'

conceptual difficulties. In evaluating the success of their teaching they focused on management and student interest and behavior rather than student learning.

Didactic teaching. Most of the teachers using the *Exploring Science* textbook regarded the text as a repository of knowledge to be taught to the students. Not suspecting the existence of student misconceptions, they remained unaware of them throughout the unit. There is no evidence that the textbook authors were aware of the misconceptions either. As a result, the teachers failed to detect evidence that their students were interpreting much of the text information in terms of their misconceptions and were having trouble understanding certain crucial new ideas. Consequently, most students remained committed to their misconceptions.

Teachers taking a didactic approach for whom case studies have been developed include Ms. Rosal (Slinger, C. Anderson, & E. Smith, 1983) and Ms. Lane (Eaton, C. Anderson, & E. Smith, 1984). Both Ms. Rosal and Ms. Lane were excellent teachers, among the best we observed. They began planning their units well before they taught, locating and reading additional information about light and its properties and searching for supplemental materials and teaching ideas. Their teaching was well organized, carefully planned, and interesting to the students.

All of these virtues, however, were not enough. Most of the students were still committed to their misconceptions about light and color at the end of the unit. Like other teachers who taught in a didactic manner, Ms. Rosal and Ms. Lane had presented the scientific conceptions in a manner that precluded expression of the children's own thinking about light. As a result, they never became aware of their students misconceptions, and their students

never became aware of the conflict between what they were being taught and their own previous ideas.

Some of the SCIS teachers also taught didactically. They followed many of the suggestions in the teacher's guide, but attempted to guide the discussions with improvised convergent questions and hints so that a story line emerged to explain the results obtained (Smith & Anderson, 1983). This tended to mask student misconceptions. Their occasional emergence went unnoticed and unchallenged.

The students' misconceptions made the story line difficult for them to follow; many could not follow it. They continued to interpret their classroom experiments in terms of their misconceptions. Although some students were able to follow this story line, they usually acquired the new concepts without reconciling them with their misconceptions. This resulted in serious distortions in the conceptions these students developed.

Discovery teaching. Several of the SCIS teachers tried to avoid telling answers to their students, encouraging them instead to develop their own ideas from the results of plant-growing experiments. In so doing, the teachers misinterpreted crucial parts of the SCIS teacher's guide, which call for direct presentation of the concept of photosynthesis during the "Invention" portion of the SCIS Learning Cycle. Ambiguities in the teacher's guide and the perception that SCIS was strictly a discovery program, however, prevented these teachers from understanding the nature of "Invention" as intended by the SCIS developers.

Most of these teachers were also unaware of the importance of the students' misconceptions and did not understand the intended function of specific teaching suggestions in challenging them. They often asked students to interpret their observations in open-ended ways when the teacher's guide suggested

questions that would lead students to consider specific theoretical issues. In the absence of direct information and feedback from their teachers, most students used their misconceptions as the basis for interpreting the plant-growing experiments. They did not develop a scientific understanding of photosynthesis as portrayed in the teacher's guide.

Ms. Howe (E. Smith & C. Anderson, in press) interpreted SCIS as a discovery program. She found it very frustrating that her students were unable to invent the concept of photosynthesis on their own, even after conducting the plant-growing experiments, and ultimately decided that the SCIS program was inadequate for teaching students about photosynthesis.

Other discovery-oriented teachers dealt with their students' failure to invent photosynthesis by concluding that the invention of photosynthesis was not the goal or main point of the unit, that the process of conducting experiments and thinking about their implications was more important than the specific scientific concepts that might be developed through that process. Although the vagueness of the teacher's guide makes this interpretation defensible, we do not believe that it is consistent with the structure of the *Communities* Unit as a whole. If students are to understand the functioning of a biological community, they must come to know that plants are producers: Plants make their own food through the process of photosynthesis.

In general, the discovery-oriented teachers became more aware of their students' misconceptions than did the activity-driven or didactic teachers. Because they lacked an adequate strategy for teaching the scientific conceptions, however, they were no more successful in helping their students undergo conceptual change. The result was that several of the discovery-oriented teachers found themselves frustrated and disturbed by the contrast between

their students' actual understanding and what they wanted their students to understand.

In contrast to the three approaches just described, a conceptual change approach intentionally addresses the problem of getting students to change their misconceptions and adopt the intended goal conceptions (see pp. 19-23). The *Exploring Science* program did not address the problem of conceptual change. While the SCIIS and SCIS II teacher's guides did reflect a conceptual change approach, none of the teachers in the Year 1 study fully implemented it. Thus the major task we faced in Year 2 of the project was designing ways to help teachers implement a conceptual change approach to teaching.

Teachers' Information-Processing Limitations

Each of the approaches to teaching we observed in Year 1 was inadequate in that it failed to produce conceptual change (see Table 1) in most students. It was clear, however, that simply providing teachers with information about their students' misconceptions or appropriate teaching techniques would not be sufficient to change their approaches to teaching. The SCIS teachers, in particular, were experiencing difficulties because they were failing to make use of information that was already in the teachers' guide.

We believe that both of the essential insights of cognitive science discussed earlier are necessary to explain this failure. The teachers' difficulties were due in part to the effects of their cognitive structures. They depended on their own previous ideas about teaching and learning as they interpreted the teacher's guide. Thus they failed to recognize the unusual and sophisticated strategy implicit in the SCIS Learning Cycle (E. Smith & C. Anderson, 1983).

The teachers' information-processing limitations also played an essential role. Teaching an activity-based program like SCIS is a complicated and multifaceted endeavor. In fact, the teachers were flooded with so much information and so many problems that they had to ignore something. Under these circumstances, it is not surprising that a discussion of the SCIS Learning Cycle in the introductory material and a few references to student misconceptions did not get the attention our results indicate they deserved (E. Smith & C. Anderson, in press).

Year 2 Results

During Year 2, we developed and field-tested improved curriculum materials. The results from the first year made clear the nature of the task to be done. We needed to develop curriculum materials that helped teachers become aware of, and responsive to, their students' misconceptions but did not increase the teachers' information-processing load.

Modifying the Program Materials

We began modifying the program materials with an understanding that although neither program was successful in inducing conceptual change, the reasons for their failure were quite different. The *Exploring Science* textbook was simple to use, but it embodied a didactic instructional strategy that was inadequate. The SCIS program, on the other hand, was based on a sophisticated strategy for conceptual change, but teachers failed to implement this strategy due to difficulties with the content and organization of the teacher's guide and the complexity of teaching activity-based science. Instead, they interpreted the teacher's guide as embodying alternate strategies (activity-driven, didactic, or discovery) that they understood better and that were simpler to use. Given the differences in the programs, we chose to modify them in different ways.

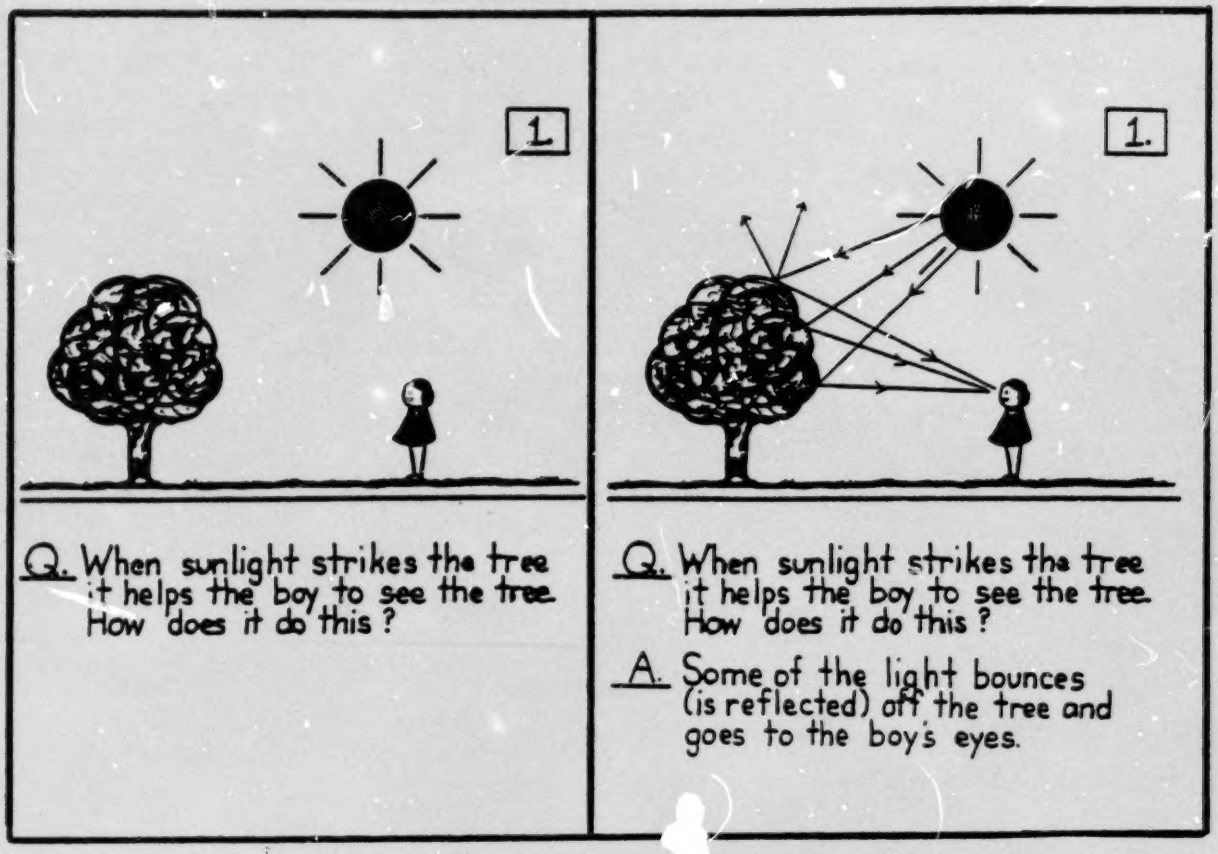
A series of 13 supplemental transparencies was created for the textbook teachers. Each transparency presented a situation and asked a question that could be answered using either the students' misconceptions or a scientific conception of light. An overlay presented a scientific answer to the question. An accompanying teacher's guide (C. Anderson & E. Smith, 1983c) described student misconceptions and contrasted them with the scientific theories. A sample page from the teacher's guide is illustrated in Figure 1.

For SCIS, modified teacher's guides were developed to clarify the instructional strategy implicit in the teaching suggestions (E. Smith & A. Anderson, 1982). The modifications were designed to (a) make the nature of student misconceptions clear to the teachers, (b) help the teachers understand how each suggested activity contributed to the development of students' understanding, and (c) reduce the information-processing demands on the teacher during planning.

Classroom Observations for Year 2

The modified materials changed the classroom behavior of both textbook and SCIS teachers.

The six textbook teachers we observed (four of whom had also been observed during the first year) commented that the transparencies and accompanying teacher's guide had helped them to clarify their understanding of what they should be teaching and why. During class they were much more likely to require students to explain their thinking about light and seeing. They also gave students more specific feedback, indicating ways in which the students' ideas about light or vision were deficient. The teachers also placed more emphasis on crucial concepts, rather than treating the contents of the textbook as a list of facts to be presented and discussed one at a time (C. Anderson & E. Smith, 1983b).


1.
Q. When sunlight strikes the tree it helps the boy to see the tree. How does it do this?
1.
Q. When sunlight strikes the tree it helps the boy to see the tree. How does it do this?
A. Some of the light bounces (is reflected) off the tree and goes to the boy's eyes.

1. How Light Helps Us to See (page 145)

Common student answers. Many of your students will probably give answers like these to the question:

"The sun shines on the tree."
"The light makes it brighter."
"You can't see in the dark."

Although these answers are not wrong, we find that children who give answers like those above often do not understand the role that *reflected light* plays in seeing. They tend to believe that we see objects directly rather than detecting light that is reflected from objects. They also commonly think of light as a condition (like warmth), rather than as a form of energy that travels through space.

Textbook answer. The arrows on the transparency make it possible for you to follow the path that light takes to the boy's eyes. Notice that the boy does not see the object directly. Instead he sees the light that is *reflected* from the tree and reaches his eyes.

Figure 1. Sample page from teacher's guide.

The four SCIS teachers, two of whom had participated in the first year of the study, reported that the revised guide made their planning easier and improved their understanding of specific teaching suggestions. We saw evidence of increased use of the teaching suggestions in their classrooms. Key questions were usually posed and all of the teachers presented information about photosynthesis at the appropriate points. However, there was considerable variation in the degree to which the teachers became aware of and directly challenged their students' misconceptions and in the emphasis placed on the invention of photosynthesis.

The teachers reflected varying combinations of hesitancy to go against their previous approach, failure to recognize indications of student misconceptions, and inadequate understanding of the functions of some of the teaching suggestions in challenging student misconceptions. These results suggest that the revised guide was more successful in limiting information-processing demands on teachers than in helping them fully implement a conceptual-change approach to teaching.

There appear to be several reasons for these results. We did not adequately anticipate the teachers' alternative views and approaches (E. Smith & C. Anderson, 1983) and, therefore, did not adequately emphasize those aspects of the guide most likely to be misconstrued or overlooked. Neither did we give adequate guidance for interpreting anticipated student responses in terms of student conceptions.

Other reasons for these results relate to the instructional strategy itself. The complexity of the strategy makes it inherently difficult to fully grasp. Also, ambiguities in the empirical results of the students' experiments made some key strategic moves less attractive to the teachers. Finally,

the strategy fails to address certain aspects of students' misconceptions, especially the underlying conception of what constitutes "food" and why.

Overall, the observed changes in the behavior of both the textbook and SCIS teachers showed movement toward a conceptual change style of teaching. The textbook teachers, in particular, were far more sensitive and responsive to their students' misconceptions during Year 2.

Student Learning for Year 2

The student test data for Year 2 showed results roughly parallel to those shown by the classroom observational data. The textbook teachers were much more successful in changing their students' conceptions of light than they had been the previous year. The results for two of the most important goal conceptions are presented in Table 2. Results for other concepts were similar (C. Anderson & E. Smith, 1983a).

Table 2
Percentage of Students Understanding Two Important Concepts About Light and Seeing

	Year 1		Year 2	
	Pretest	Posttest	Pretest	Posttest
People's eyes detect reflected light.	5	22	6	78
People see the colors of reflected light.	2	14	2	39

The analysis of SCIS data shows no overall improvement in student learning between the two years. We attribute this to several factors. As discussed above, the revised guide was only partially successful in improving

teachers' awareness of students' misconceptions and the role of specific teaching suggestions in challenging them. Beyond this, however, there is evidence that a deeper misconception about what constitutes food for plants existed that was not addressed by the SCIS strategy (Roth, E. Smith, & C. Anderson, 1983). Although students may come to believe that plants make food, they do not see that as inconsistent with the plants also taking in food from other sources. The contrast between the first and third rows of Table 3 illustrates the number of students who fell into this category. The SCIS strategy does not provide a basis for rejecting the idea that any materials plants take in from their environment constitute food.

A further problem is reflected in the second row of Table 3. Few of the students understood the relation between light and the making of food. The strategy in the SCIS unit requires that students come to view light as essential for plants to survive. The ambiguity in the empirical results the students obtained in their experiments appeared to move some students away from this belief. (In the hands of fifth graders, it was not unusual for plants grown in the dark to live as long as plants grown in the light). Our suggestions to help reduce this ambiguity in Year 2 did not result in much improvement. For experiments to play their intended role in conceptual change, the results must be clear and reliable. Ambiguity in classroom discourse and loose framing of the issues in teacher questions also contributed to the problem (E. Smith & Lott, 1983).

SCIS Year 3 Results

Although not a part of the PTIS Study, a subsequent study was conducted that involved a more fundamental revision of the SCIS strategy. Kathleen Roth developed a unit (*Food For Plants*) that used the SCIS investigations but also

Table 3
Percentages of Students Reflecting Understanding of Important Concepts About Plant Growth

	Year 1		Year 2	
	Pretest	Posttest	Pretest	Posttest
Plants do not take in food from their environment, they make it.	1	6	1	11
Plants make food only in the light.	2	17	2	15
Plants make food.	9	58	16	56

included text materials and expanded use of student writing to attack directly the students' underlying misconceptions about food and to improve student understanding of the nature of scientific explanations (Roth, 1983). Also, teaching suggestions were integrated into these materials in ways that reduced the information-processing load on teachers. These materials were used with three classes by a teacher who had participated in Years 1 and 2 of the study. Preliminary analysis of the results indicates that there were substantial changes in both teacher behavior and student learning; these changes were comparable in magnitude and direction to those obtained in Year 2 for the textbook teachers (Roth, in press).

Discussion

The study reported here and the related conceptual-change research warrant at least tentative acceptance of the following assumptions about teaching and learning.

1. Students often have misconceptions that differ in important ways from the scientific conceptions teachers want students to learn.

2. Students' misconceptions influence students' behavior and interpretation of instruction.

3. If instruction does not take these misconceptions into account, many students will misinterpret instruction in ways that interfere with intended learning.

4. Teachers' use of instructional materials reflects teachers' conceptions of teaching and learning, teachers' patterns of planning and resulting information needs, and features of the materials themselves.

5. Few materials take into account the existence, much less the specific features, of student misconceptions. Few teachers have a conceptual-change conception of teaching and learning. They therefore usually have difficulty in interpreting instructional materials and suggestions that reflect this conception.

These claims point toward a new relationship between research and practice. Indeed, the results of this project are a demonstration of the potential of this new relationship for improving teaching and learning. Research examining students' misconceptions and experience of instruction on a particular topic can be used to develop strategies and materials that are much more successful in bringing about student learning of scientific conceptions. Further, research examining teachers' conceptions of teaching and learning, use of materials in planning, and information needs can be used to develop instructional materials that communicate effectively to teachers and that teachers can effectively use.

This study and related research on conceptual change have implications for curriculum development. Foremost, this work implies that the cognitive science-based tools now available enable significant improvement in teaching and learning through appropriate research and development of instructional materials and strategies. More specific implications are described below in terms of (a) necessary or desirable features of instruction, (b) knowledge needed by teachers, and (c) desirable features of instructional materials.

Desirable Features of Instruction

This section is based on the requirements for conceptual change proposed by Posner, Strike, Hewson, and Gertzog (1982). For instruction to be successful in achieving conceptual change, it must meet each of these requirements. Posner and his colleagues and others (Hewson, 1981; Nussbaum & Novick, 1982) have suggested tactics for achieving these requirements. We do not reiterate all of their points here, but rather emphasize some of them and make additional points emerging from our own work.

We believe that the successes we have had in achieving conceptual change in relatively large proportions of the students we tested and observed are a reflection of the success of the instruction in meeting these requirements. While our analyses do not enable us to determine with certainty which aspects of instruction were primarily responsible, the following paragraphs represent our best interpretation of the mechanisms by which this success was achieved.

Instruction should lead students to become dissatisfied with their misconceptions. In the instructional materials we developed and the successful instruction we observed, this requirement has been addressed primarily through posing questions to draw out anticipated misconceptions, directly challenging anticipated misconceptions, and explicitly contrasting anticipated misconceptions with the scientific alternatives.

Consistent with suggestions in the literature, the successful instruction has posed questions designed to draw out anticipated student misconceptions. These questions frequently required students to make predictions and give explanations of specific phenomena. Such "exposing events" (Nussbaum & Novick, 1982) increase both the teacher's and students' awareness of the students' misconceptions.

The successful instruction included direct challenges to anticipated student misconceptions. Such challenges involved developing and discussing experimental results contrary to student predictions, focusing questions on aspects of phenomena not explained by the students' misconceptions, and pointing out inconsistencies between aspects of students' misconceptions and other knowledge. The successful instruction also emphasized direct and explicit contrasting of the students' misconceptions with the scientific alternatives. Frequently, these contrasts involve juxtaposing student explanations with scientific explanations of specific phenomena being considered.

In summary, the successful instruction included many instances in which anticipated misconceptions were brought out and challenged. In our judgement, these instances were successful in leading many of the students to become dissatisfied with their misconceptions. Many of these instances may also have contributed to the instruction meeting some of the other requirements as well.

Instruction should develop an initial, minimal understanding of the scientific conception. This requirement does not imply that a minimal understanding is all that is sought, but rather that students must construct an adequate initial representation of the scientific conception as a basis for comprehending further information about it and differentiating between it and their misconceptions. Helping students accomplish this crucial step is particularly difficult and, we believe, a point at which instruction often breaks down. Students often either (mis)interpret information about the new conception in terms of their misconceptions, find it unintelligible and ignore it, or merely memorize the information to pass a test.

The successful instruction made the new scientific conception explicit in some form. While this always involved some verbal expression, the "invention"

(Knott et al., 1978) also sometimes included diagrammatic representations or analogies. Successful instruction always involved presentations in which the scientific conception was emphasized and not just presented as one of many equal pieces of information. The major presentations of the scientific conceptions were usually in the context of applications to phenomena with which the students had already developed some familiarity. Furthermore, the students were frequently required to immediately apply the new scientific conception in attempting to explain those phenomena. These applications helped students make sense of the scientific conception and provided teachers with feedback on the students' comprehension. Teachers then provided students with corrective feedback. The successful teachers usually gave carefully developed explanations of the conception we had suggested they emphasize. For the *Food for Plants* unit (Roth, 1983), the successful teacher included in her presentation explicit attention to likely misinterpretations of the scientific conception.

The successful instruction usually included several opportunities for the students to develop an initial minimal understanding of the new scientific conception. So important was this step that the major presentation and the application to familiar phenomena were repeated more than once. In addition, students had opportunities to refine their understanding as the scientific conception was applied to new situations. Such applications are discussed further in the section on developing the students' sense of the fruitfulness of a scientific conception.

Instruction should make the scientific conception plausible. A new scientific conception may initially strike a student as implausible. The student might then dismiss it out of hand or reinterpret it inappropriately in an

effort to make it more plausible. Thus this requirement is closely related to the previous requirement. The emphasis on applying the new scientific conception to familiar phenomena together with success in overcoming misinterpretations appear to have enabled the successful teachers to make these scientific conceptions plausible to their students.

Our analyses of instruction and the students' conceptions have identified potential sources of counterintuitiveness that could be used in future instructional efforts. For example, students sometimes find the idea that people see objects by detecting light reflected from them implausible because they don't believe that non-shiny objects reflect light. Development of the idea that even non-shiny objects reflect light (diffusely) would be useful in making the new conception more plausible. Anticipation of ways in which a new scientific conception might be counterintuitive can help a teacher teach better.

Instruction should increase the students' sense of the scientific conception's fruitfulness. Even when students do develop minimal understanding of a new scientific conception and find it plausible, they may continue to use their misconceptions to organize and interpret any new information or phenomena that they encounter. Students must come to sense the fruitfulness of the scientific conception if they are to choose it as the basis for further thinking. The successful instruction included opportunities for students to apply the scientific conceptions to a variety of situations in such a way that the relationships between the scientific conception and its applications were made explicit.

It takes a lot of effort. In these paragraphs we have described features of instruction that was successful in achieving intended changes in the

conceptions of a relatively large proportion of the students in the participating classes. This success was achieved only after considerable effort to determine the obstacles to student learning and to provide teachers with means to improve their instruction. While much remains to be done to further understand these features of instruction and their contributions, we feel that the success achieved to date warrants continued work.

Knowledge Needed by Teachers

Any kind of teaching requires knowledge on the part of the teacher and those who develop materials for teachers. However, various approaches to teaching require different kinds and amounts of knowledge.

The activity-driven approach described earlier requires knowledge of what students are to do and procedures for getting them to do it. Detailed knowledge of the learning goals and the learning functions of particular activities are not essential.

The discovery and didactic approaches require not only knowledge of activities but knowledge of the functions of those activities in relation to specific learning outcomes. While the didactic approach requires detailed knowledge of content to be presented and a story line that connects this content, the discovery approach requires detailed knowledge of the observations that will form the basis for student discovery of new concepts.

Teaching for conceptual change is unique in requiring knowledge of students' misconceptions, the goal conceptions that students are to develop, and the pedagogical tools by which students will be encouraged to give up their misconceptions and construct and develop commitment to more scientific alternatives. In the following paragraphs we elaborate the knowledge requirements implied by the features of instruction described in the previous section.

While all of this knowledge is interrelated, we have organized the presentation in terms of knowledge of content, knowledge of students, and knowledge of activities.

Knowledge of content. Teaching for conceptual change requires sound knowledge of the topic under study. In particular, it requires understanding the organizing conceptions underlying the topic and a variety of applications of those conceptions to specific phenomena. Rather than being organized as a string of facts as was typical in the didactic approach to teaching, knowledge of the topic is organized around basic underlying conceptions. The development of student understanding of these basic conceptions is the primary learning goal of instruction. Thus knowledge of these particular goal conceptions, as distinguished from a variety of auxiliary information, is essential.

The instruction characterized in the previous section makes considerable use of applications of the goal conception to various phenomena. Such instruction requires knowledge of these applications. Furthermore, it is essential that the teacher understand specifically how the goal conception applies to these phenomena, a condition often not met in the less successful instruction we observed.

While this knowledge of content has been described in isolation from our characterization of required knowledge of students, in practice, the goal conceptions and applications are understood more completely in terms of their contrast with student misconceptions.

Knowledge of students. While all of the approaches to teaching described here require some knowledge of how students will typically respond to instruction, conceptual-change instruction is unique in requiring knowledge of the

nature of the misconceptions students bring with them to instruction and the manifestation of those misconceptions in applications.

Knowledge of the kinds of explanation that students tend to give is also important. For example, student tendencies to explain phenomena in terms of empirical factors that constitute, in essence, circular reasoning (as when students explain that plants need light because they can't live without it), need to be contrasted with the kinds of explanation represented by application of the goal conception. These explanatory tendencies are part of the prior knowledge or "conceptual ecology" (Strike & Posner, 1982) that students bring with them to instruction. It may be necessary to take into account such tendencies or even change them in order for the intended conceptual change to occur. Indeed this might be viewed as a form of conceptual change in itself.

The knowledge of content and students' misconceptions together represent knowledge of the goal of conceptual change teaching. That is, they represent detailed knowledge of the changes to be brought about through instruction.

Knowledge of activities. In contrast to activity-driven teaching, conceptual-change teaching requires more than simple knowledge of what to do and how to do it. Conceptual-change teaching requires knowledge on which to base diagnosis and interpretation of the significance of student behavior and appropriate contingent teaching strategies. To be successful, conceptual-change teachers must know when and how to apply each of the strategies just described, and they must do so while successfully coping with all of the normal demands of classroom management and organization.

Desirable Features of Instructional Materials

The instructional materials available to the teachers we observed were not well suited to conceptual-change teaching. They either failed to address

the problem of conceptual change or failed in their effort to communicate necessary information to teachers. In our efforts to help teachers more successfully promote conceptual change, we developed materials that, in addition to reflecting conceptual-change strategies, addressed the goals of (1) providing teachers with needed information, (2) limiting information processing demands on the teacher to realistic levels, and (3) promoting conceptual change in teachers as they used the materials. Feedback from teachers and increased student learning indicate that these goals were achieved to a significant extent. In the following paragraphs we will describe the features of the instructional materials that addressed these goals.

Instructional materials should provide information needed by teachers.

The instructional materials we developed made explicit information about content, students, and activities. The materials provided information about goal conceptions and their applications to phenomena, expected student responses to diagnostic questions and aids to interpretation of students' misconceptions, contrasts between students' misconceptions and goal conceptions, and various specific teaching suggestions to help promote conceptual change in students. Also made explicit were the functions of the suggested teacher behavior in the conceptual-change process. For example, the purpose of particular questions in bringing out or challenging student misconceptions was indicated.

While inclusion of this information within the instructional material was necessary, simply making it explicit was not sufficient. Our research indicated that if teachers were to have access to this information, it would have to be presented so as to not produce an information overload.

Instructional materials should not overload the teacher's information-processing capacity. One way we addressed the need to limit information-processing demands on the teacher was to include information in materials directly used by students whenever possible. For example, we built diagnostically useful questions into overhead transparencies (C. Anderson & E. Smith, 1983c) and a student text (Roth, 1983). Freed from having to think about the specific wording of the questions, teachers could focus their attention on student responses. Formulations of the goal conception were also included in the student materials. In some instances, information about anticipated student misconceptions was also included in student materials along with explicit contrasts between these and the goal conceptions (Roth, 1983).

Information needed only by the teacher was organized and located according to whether it would be needed for long-term, weekly, or daily planning and preparation. Information was presented in clearly identified and stable locations within the materials. Whenever possible, information was located in portions of the materials that the teacher would be using when the information was needed. For example, information about anticipated responses to diagnostic questions was included near the statement of the questions in the teacher's version of the student materials (Roth, 1983).

The large volume of information required for a given unit led us to break the instruction down into meaningful segments or chunks. The organization and rationale for each unit could be understood in terms of the chunks and their interrelationships. However, the detailed information relevant to each chunk could be dealt with one chunk at a time. For example, a three-week investigation in the SCIS unit was broken down into a series of lessons and activities. This organization was presented as an overview of the investigation along with

a brief narrative description of the strategy for the chapter and the function of the activities in bringing about a specific change in student conceptions. However, the detailed teaching suggestions were presented on an activity by activity basis.

In some instances, the inherent complexity of activities made teaching them especially difficult. In such cases we simplified the activities in ways that would not compromise their major instructional contributions.

In sum, these features of the instructional materials were incorporated to allow us to communicate additional information to teachers while at the same time limiting or even reducing information-processing demands.

Instructional materials should promote conceptual change in teachers. Teachers' interpretations of instructional materials are governed in part by their conceptions of teaching and learning. Thus to have access to the information in the teachers' guide and to incorporate suggested features in instruction, the teachers must develop a conceptual-change conception of teaching. The teachers' use of the teachers' guide must help teachers develop this conception as distinct from the activity-driven, discovery, or didactic conceptions with which they might otherwise interpret the suggestions. The instructional materials were designed to promote such conceptual change through both use of the materials per se and through the interpretation of student behavior.

A conceptual-change conception of teaching and learning is built into the very fabric of the instructional materials. The learning goals are stated as desired conceptual changes, and both probable student misconceptions and goal conceptions are made explicit. The function of activities and teaching strategies in promoting conceptual change in the students is also made explicit.

While these features are important, we believe the most powerful device for promoting conceptual change in teachers lies in helping them interpret student responses.

The instructional materials that we have developed make use of a feedback loop, which begins with the diagnostic question included in the student or class materials. The accompanying teacher materials provide information about anticipated student responses and their significance in terms of student conceptions. The teachers are thus enabled to perceive student conceptions, including misconceptions, in the students' responses. This increased awareness of student conceptions, together with information about the contrast between student misconceptions and the goal conception, form the basis for the teachers' understanding of the instructional goals and the intended function of various teaching suggestions. We have observed that teachers using the materials have been able to improvise and supplement the suggested strategies as needed to encourage student learning.

As implied, we do not view it as essential that teachers complete this important conceptual change before beginning to use the materials. Rather, this process can continue gradually as teachers use the materials in conducting instruction. Although inservice education can undoubtedly contribute to the conceptual-change process, it need not carry the entire burden. Further research will be needed to determine the potential contributions and cost effectiveness of these two means of promoting teacher development for conceptual change teaching.

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Appendix

Annotated Bibliography of Publications Based on the Planning and Teaching Intermediate Science Study (PTIS)

Publications Currently Available in the Research Series of the Institute for Research on Teaching (IRT)

R.S. 89 The task features analysis system. N. Landes, E.L. Smith, & C.W. Anderson, 1981. $2.50

This manual describes the system used to analyze teacher' guides for the PTIS Study. Each section of the teacher's guide is broken into a series of classroom tasks, and key features of those tasks are described in a way that facilitates comparison with observed classroom instruction.

R.S. 90 An instructional system for observing and analyzing elementary school science teaching: A user's manual. R. Hollon, C.W. Anderson, & E.L. Smith, 1981. $3.50

This manual describes the classroom observational procedures used for the PTIS Study. Instruction is divided into a series of classroom tasks, and both narrative and coded data are produced. In conjunction with R.S. 89, this manual can be used to produce systematic comparisons between classroom instruction and the teacher's guide on which the instruction is based.

R.S. 172 Plants as producers: A case study of elemenary science teaching. E.L. Smith & C.W. Anderson, 1983. $3.00

(An edited version of this report has been accepted for publication in the Journal of Research in Science Teaching.)

This paper reports a case study of a teacher trying to teach her students about photosynthesis using materials from the Science Curriculum Improvement Study (SCIS). It describes her attempts to implement what she viewed as the activity-based, discovery teaching strategy of SCIS, and her growing disillusionment as she found that the students consistently failed to interpret results of their experiments as she had anticipated. It shows how a knowledge of the students' misconceptions makes their reactions understandable and how the teacher's interpretation of the SCIS teaching strategy prevented her from taking actions that might have helped the students overcome their misconceptions. An analysis of the difficulties created by the style in which the SCIS teacher's guide is written and suggestions for improvement are included.

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* To order, please send check, money order, or prepaid purchase order (payable to Michigan State University) to IRT Publications, 252 Erickson Hall, Michigan State University, East Lansing, MI 48824-1034. Michigan residents should add a 4% state sales tax to all orders. Foreign orders must be paid by either an international money order or a check drawn on a U.S. bank. Please allow four to six weeks for delivery.

R.S. 128 Students' misconceptions interfere with learning: Case studies of fifth-grade students. J.F. Eaton, C.W. Anderson, & E.L. Smith, 1983. $3.00

(An edited version of this report, which is based on a paper presented at the 1982 convention of the National Association for Research in Science Teaching (NARST), has been accepted for publication in The Elementary School Journal.)

The report focuses on the difficulties experienced by six students, three in one classroom and three in another, who were studying light. It describes the students' misconceptions about light, and it shows how the treatment in the textbook the students were using (Laidlaw Brothers Exploring Science) and the instructional methods used by the teachers failed to overcome most of those misconceptions. The report concludes with suggestions for improving textbook development and teaching methods.

R.S. 129 Studying light in the fifth grade: A case study of text-based science teaching. L.A. Slinger, C.W. Anderson, & E.L. Smith, 1983. $3.25

This report describes the planning and teaching methods used by one teacher using the Laidlaw Brothers' Exploring Science text. She was a highly enthusiastic teacher who used a variety of methods to enrich her students' experiences and make them interesting. However, because she viewed learning as a process of adding knowledge to what her students already knew, and because the textbook failed to inform her about common student misconceptions, she never became aware of some of her students' most important problems, and her students ended the unit without understanding certain key concepts concerning the nature of light and how people see.

R.S. 130 Transparencies on light: Teacher's manual. C.W. Anderson & E.L. Smith, 1983. $3.00

This manual illustrates and describes how to use the 13 transparencies that form the basis for the successful treatment conducted during the second year of the PTIS Study. Each transparency is illustrated. An accompanying commentary contrasts common student answers to the questions asked on the transparencies with the scientific answers provided in the Laidlaw Brothers Exploring Science textbook. A series of tables at the end of the manual describe common student misconceptions about light and contrast them with scientific conceptions.

R.S. 139 Ways of going wrong in teaching for conceptual change. E.L. Smith & C.W. Lott, in press. $4.00

This paper reports a case study of a teacher trying to teach her students about photosynthesis using a revised teacher's guide designed to make the SCIS strategy more explicit. It describes the strategy in detail, noting the ways it anticipates and addresses student misconceptions. It describes the very limited changes that occurred in students' conceptions and then identifies and discusses several aspects of the instruction that account for the

disappointing results. The discussion emphasizes detailed analysis of the teacher's questions and students' responses to them. (The research upon which this report was based was supported in part by a grant from the National Institute of Education.)

Publications in Books and Journals

Anderson, C.W., & Smith, E.L. (1984). Children's preconceptions and content area textbooks. In G.G. Duffy, L.R. Roehler, and & J. Mason (Eds.) Comprehension instruction: Perspectives and suggestions. New York: Longman, 187-201.

This chapter presents results of the PTIS study from the perspective of student comprehension of instruction. It discusses the role of student preconceptions in comprehension and describes two case studies (documented in more detail in R.S. 127 and R.S. 129) that depict the failure of discovery and didactic approaches to teaching in achieving student learning of scientific concepts. It also describes the modified teaching materials we developed and preliminary results from their use.

Eaton, J.F., Anderson, C.W., & Smith, E.L. (1983). When students don't know they don't know. Science and Children, 20(7), 7-9.

This article is a nontechnical description of the project, emphasizing the role of student misconceptions in the problems teachers encountered with student learning of science concepts. It describes our efforts to help teachers by providing modified instructional materials and the results on student learning. It also suggests ways in which teachers can begin to address the problems posed by student misconceptions.

Eaton, J.F., Anderson, C.W., & Smith, E.L. (1984). Students' misconceptions interfere with science learning: Case studies of fifth-grade students. The Elementary School Journal, 84(4), 365-379.

(See note for IRT Research Series No. 128)

Roth, K.J., Smith, E.L., & Anderson, C.W. (1984). Verbal patterns of teachers. In G.G. Duffy, L.R. Roehler, & J. Mason (Eds.), Comprehension Instruction: Perspectives and suggestions. New York: Longman.

This chapter describes and compares four teachers in terms of the patterns of verbal interactions that characterized their science classes. The unique patterns of the one teacher who was successful in helping a majority of her students understand a new science concept are identified. The article presents and discusses a model that characterizes patterns of verbal interaction for five different steps or stages of instruction to promote student comprehension in content areas.

Roth, K.J. (in press). Using classroom observations to improve science teaching and curriculum materials. In C.W. Anderson (Ed.), 1984 yearbook of the Association for the Education of Teachers in Science. Columbus, OH: ERIC Center for Science, Mathematics and Environmental Education.

This chapter presents a case study following a teacher through three years of teaching a unit on photosynthesis. She participated in the PTIS study using the SCIIS teacher's guide in Year 1 and our revised guide in Year 2. The chapter describes how an improved understanding of both student and teacher thinking about this unit was used in a follow-up study to develop a student text/workbook and teacher's guide to accompany the unit. It also describes how the teacher's thinking and teaching changed in Year 3, resulting in substantial improvement in student learning.

Smith, E.L., & Anderson C.W. (in press). Plants as producers: A case study of elementary science teaching. Journal of Research in Science Teaching.

(See note on IRT Research Series No. 127)

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